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PAPER

Achieving Fairness over 802.11 Multihop Wireless Ad Hoc Networks

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SUMMARY IEEE 802.11 MAC protocol for medium access control in wireless *Local Area Networks* (LANs) is the *de facto* standard for wireless ad hoc networks. However, it does not perform well in terms of fairness, delay and throughput specially, in multihop networks. The problem is due to both the MAC and link layer contentions. Many research papers have been published in these fields. Among them, a modification of IEEE 802.11 MAC protocol was proposed to achieve per-node fairness, but modifications to the original MAC layer requires a change of hardware, therefore, it is difficult to implement. Moreover, it fails to solve the per-flow unfairness problem. In this paper, we propose a new scheduling method, *Probabilistic Control on Round robin Queue* (PCRQ) scheduling, aiming to achieve per-flow fairness in multihop ad hoc networks. PCRQ scheduling in the link layer is proposed without modifying IEEE 802.11 MAC protocol. Our proposed method achieves good performance results in both UDP and TCP traffic.

key words: *fairness, multihop wireless, PCRQ scheduling, scheduling algorithm*

1. Introduction

In a multihop ad hoc network, stations communicate with each other using multihop wireless links and there is no stationary infrastructure such as a base station. Each station in the network also acts as a router, forwarding data packets from other stations. For example, a group of people with laptops with a wireless *Network Interface Card* (NIC) with 802.11-equipped may gather together for voice or video conferences at their company building. In order to transfer voice, video data, share documents to far colleagues, they could cooperate with each other by switching their NICs to ad hoc mode. The ad hoc network also can integrate with stationary infrastructure networks through a gateway to use the services in the global Internet or to be reached by another terminal in the global Internet. However, IEEE 802.11 MAC protocol [1], the *de facto* standard for wireless ad hoc networks was not suitably for multihop network. In asymmetry topologies, as each station's offered load approaches the saturated value, the performance of IEEE 802.11 in terms of delay, fairness degrades dramatically [2], [3]. In multihop network, stations cooperate to forward packets from other stations. A station not only transmits the direct flow, which is generated by the station, but also forwarding flows, which are generated by the neighboring stations. Moreover, the station also shares the channel capacity with them. The effect of the contentions in the MAC and link layers affects the performance of the network. In the MAC layer, each station contends for using bandwidth. Due to the MAC layer contention, the allocated bandwidth for sending and forwarding packets cannot ensure per-flow fairness [2], [3]. In the link layer, there is contention between the direct flow and forwarding flows for the buffer space. Obviously, the direct flow gets more advantage than forwarding flows [4]–[6].

In our research, we consider both UDP and TCP traffic. In UDP traffic, packets may arrive out of order, appear duplicated, or go missing without notice. UDP does not adjust the offered load, even when some packets are dropped by the MAC layer contention. Thus the direct flow gradually but completely starves forwarding flows from neighboring stations. The network becomes totally unfair. TCP reacts better to the congestion than UDP. In the congestion, TCP performs a congestion control algorithm to decrease the traffic rate. However, there are still many packets in competing in bandwidth and TCP flows suffer from fairness problem.

In this paper, we propose *Probabilistic Control on Round robin Queue* (PCRQ) scheduling, in which we use an individual queue for each of the direct and forwarding flows, each queue is served as *Round Robin* (RR) fashion. In the link layer, we propose three algorithms to control the number of input packets to a queue, the turn of reading queues in RR fashion, and the number of output packets from a queue. By controlling input packets, heavy offered loads can be reduced. Controlling the turn of reading queues will help flows with small offered load get more chance to send packets. Moreover, by controlling output packets, number of sending packets from heavy offered load flows is reduced, and then more bandwidth will be used for receiving forwarding flows. Thus, PCRQ scheduling can improve the MAC layer fairness and achieve per-flow fairness without modifying the 802.11 MAC layer protocols. In addition to per-flow fairness, PCRQ scheduling archives positive impact in terms of the effective buffer resource and delay time. We use the Network Simulator (NS) [7] to evaluate our proposed method in some unfairness situations relying on asymmetry topologies as chain stations, complex stations and different traffic types. Fairness between multihop flows on the way to a destination and other network performances are examined. The rest of the paper is organized as follows: Section 2 compares with related works. Section 3 shows a serious unfairness problem in multihop network explain-

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ing why FIFO scheduling and also RR scheduling fail to achieve good fairness. Section 4 describes PCRQ scheduling. Section 5 evaluates our proposed method by comparing with FIFO, RR schedulings and Shagdar's method [5] in both UDP and TCP traffic. The parameters of our proposed method are discussed in Sect. 6. Finally, Section 7 concludes the paper.

2. Related Work

The fairness performance at the MAC layer has been an active research field in the past several years. The protocols MACA [8] and its extension MACAW [9] use the four-way RTS/CTS/Data/ACK handshake signals to reduce collisions caused by hidden terminals in the network. The protocol MACAW has been standardized in the IEEE 802.11 [1] as *Distributed Coordination Function* (DCF). However, the RTS/CTS scheme in DCF does not solve all unfairness bandwidth in case of asymmetric links. Several schemes for improving the fairness of MAC protocols have been proposed in the literature [10]–[12]. Moreover, Li et al. [13] investigated *Extended Inter-Frame Spacing* (EIFS) problem, i.e., the fixed EIFS value leads to unfair bandwidth allocation for each stations. They proposed flexible EIFS values based on a measurement of the length of *Sensing Range* (SR) frame.

Improved fairness of the MAC protocol will certainly improve per-flow fairness as well. However, a major problem of the MAC layer fairness solutions is difficult to implement. As the IEEE 802.11 standard is the *de facto* standards for ad hoc network and has been widely accepted by the industry. In addition, all stations in an ad hoc network require having a consistent MAC protocol. Thus, any modification of the MAC protocol results in update at all stations.

Jangeun et al. [4] pointed out the weak point of FIFO scheduling in multihop networks and proposed various queuing schemes. Each scheme has offered different degree of fairness. However, their research is based on the ideal MAC layer fairness assumption, which cannot be satisfied. Therefore, their schemes do not give good performance in the real networks. Shagdar et al. [5] and Izumikawa et al. [6] also focused on the contention of direct flow and forwarding flows, and proposed scheduling algorithms by using RR mechanism. The DCF mechanism are modified in [5] to achieve the bandwidth utilization by sending all the packets at the head of RR queues continuously without delay by back-off algorithm. However, in their solutions, the same problem as in [4] is due to the unsatisfactory assumption that the MAC layer gives fair bandwidth allocation. We will show in next section that is impossible to achieve good fairness by using only RR scheduling.

The performance of TCP over wireless networks with IEEE 802.11 medium access also has been studied extensively. The effect of TCP congestion window limits on performance of multihop networks has been evaluated in [14]–[16]. They conclude that TCP window size actually grows much larger than the optimum. There are too many packets on the path, which are competing for the same medium. It results in performance degradation and unfairness. Besides the schemes described above, there are also some other TCP enhancement schemes based on modification of the IEEE 802.11 MAC protocol [17], [18]. By modifying the IEEE 802.11, these schemes are shown to improve per-flow fairness of TCP traffic to some degree. Unlike those works on TCP over multihop wireless networks, our solution will not require significant modification to TCP or IEEE 802.11 MAC protocol. It works on the link layer, generally improves per-flow fairness in both TCP and UDP traffic.

3. Serious Unfairness Problem

We will examine the MAC and link layer contentions how they affect the per-flow fairness. There are some kinds of unfairness problem topologies. In this section, one basic multihop wireless network topology will be illustrated as an example. Consider the topology in Fig. 1, there are three stations. Stations M1 and M2 are in one transmission range, in which a packet can be transmitted and received successfully. Station M1 and gateway GW are also in another transmission range. Station M2 and GW are out of transmission range but in carrier-sensing range, in which a transmission can be detected. The carrier-sensing range is larger than the transmission range, and may be more than two times of the transmission range [19]. It is noted that the sizes for the transmission and carrier-sensing ranges vary according to the power levels. Stations M1 and M2 are assumed to generate the same offered load G to GW. Let B be the maximum medium bandwidth, and B_1, B_2 be the allocated bandwidth for stations M1 and M2 in the saturation state, respectively. We have $B = B_1 + B_2$.

3.1 MAC Layer Contention

The MAC layer contention for a station is defined as the contention in the MAC layer between the allocated bandwidth for the station B_1, which is considered as the sending bandwidth of the station, to the allocated bandwidth for its neighboring stations B_2, which is considered as the receiving bandwidth of the station. We call B_1 the sending bandwidth and B_2 the receiving bandwidth. In this topology, the serious unfairness problem in the MAC layer is due to the EIFS problem [13], which is described in Fig. 2.

At the last state of four-way handshaking process from station M1 to GW, GW sends an ACK frame in reply to a

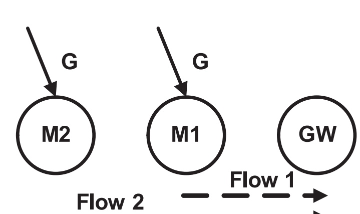

Fig. 1 A basic multihop wireless network model.

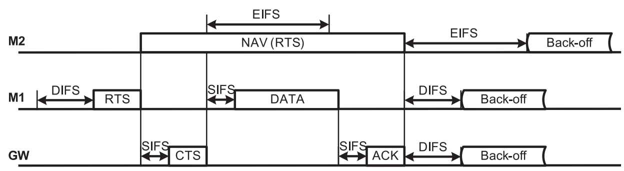

Fig. 2 Unfairness in bandwidth due to EIFS problem.

data frame from station M1, station M2 detects the ACK frame, but cannot decode it. Therefore, station M2 must wait an EIFS before accessing the channel, while station M1 waits a DIFS, which is much shorter than the EIFS. Li et al. [13] has proved that the EIFS problem leads $B_1 : B_2 \approx 4 : 1$ in this topology. In addition, the physical layer capture mechanism [20] also affects the proportion of the sending bandwidth B_1 to the receiving bandwidth B_2. When stations M1 and M2 send packets at the same time, the packet from station M2 will be ignored by station M1 because its power is lower than the other. Because the throughputs of forwarding flows are limited by B_2, the fairness between forwarding flows and the direct flow is not achieved.

Next, we will explain this problem in detail.

3.2 Link Layer Contention

The link layer contention is defined as the contention between forwarding flows and the direct flow in the outgoing buffer space. We will examine the link layer contention in the FIFO and RR scheduling methods from the topology illustrated in Fig. 1. Let the offered load G vary from zero to maximum medium bandwidth B, the individual throughput $Th(flow\,1)$ and $Th(flow\,2)$ from stations M1 and M2, respectively, are calculated in both FIFO and RR scheduling methods.

3.2.1 Link Layer Contention in FIFO Scheduling

First, if the bandwidth B is sufficiently large compared to the sum of all flow's offered loads, each flow can get its required throughput.

$$Th(flow\,1) = Th(flow\,2) = G, \quad \text{if } G < \frac{B}{3} \tag{1}$$

Second, if the bandwidth B is not enough for all flows, because B_1 is much greater than B_2, the flow 1 can get required throughput, and the remaining bandwidth is used for the flow 2. Throughputs of the flow 1 and flow 2 are calculated as follows.

$$\begin{cases} Th(flow\,1) = G \\ Th(flow\,2) = \dfrac{B-G}{2} \end{cases} \quad \text{if } \frac{B}{3} \leq G < B_1 - B_2 \tag{2}$$

Third, the network is in the saturation state. In FIFO scheduling, a common queue is used for all flows. We assume that buffer size is infinite. The ratio of the buffer allocation $Q_{flow\,1}$ for the flow 1 to $Q_{flow\,2}$ for the flow 2 at station M1 is $Q_{flow\,1} : Q_{flow\,2} = G : B_2$. Hence, the throughputs of the flow 1 and flow 2 at station M1 are calculated as follows.

$$\begin{cases} Th(flow\,1) = B_1 \dfrac{G}{G+B_2} \\ Th(flow\,2) = B_1 \dfrac{B_2}{G+B_2} \end{cases} \quad \text{if } G \geq B_1 - B_2 \tag{3}$$

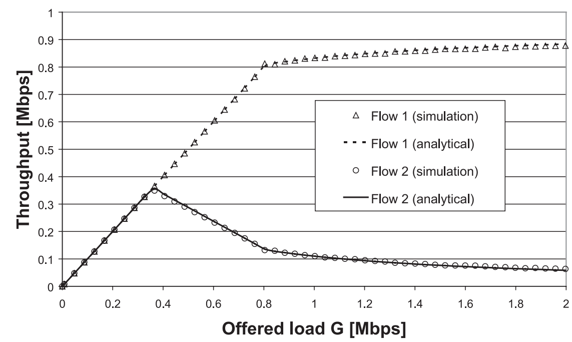

Fig. 3 Throughputs in FIFO scheduling.

Table 1 Parameters in the simulation.

Channel data rate	2[Mbps]
Antenna type	Omni direction
Radio Propagation	Two-ray ground
Distance between stations	200[m]
Transmission range	250[m]
Carrier Sensing range	550[m]
MAC protocol	IEEE 802.11b (RTS/CTS is enable)
Connection type	UDP/CBR
Buffer size	100000[packet]
Packet size	1[KB]
Simulation time	100[s]

We show in Fig. 3 the throughputs of the flow 1 and flow 2 of FIFO scheduling in simulation by NS-2 [7] and our analysis. The simulation parameters are shown in Table 1. In the simulation, the channel data rate is set with 2[Mbps], leading to the bandwidths B, B_1 and B_2 are about 1.074[Mbps], 0.939[Mbps] and 0.135[Mbps], respectively due to the overhead in IEEE 802.11 [21]. When the offered load increases, the throughput of the flow 1 comes to B_1, while the throughput of the flow 2 comes to zero. Thus, the network is totally unfair.

3.2.2 Link Layer Contention in RR Scheduling

In RR scheduling, we have the same results as in the first and second cases as in (1) and (2) described in Sect. 3.2.1. In the third case, the flow 1 and flow 2 share the bandwidth, but the throughput of the forwarding flow 2 $Th(flow\,2)$ is limited by the receiving bandwidth B_2, and the flow 1 can get all remaining bandwidth. The throughputs for the flow 1 and flow 2 are calculated as follows.

$$\begin{cases} Th(flow\,1) = B_1 - B_2 \\ Th(flow\,2) = B_2 \end{cases} \quad \text{if } G \geq B_1 - B_2 \tag{4}$$

Those RR scheduling's throughputs in simulation and our analysis are shown in Fig. 4. The result shows that RR

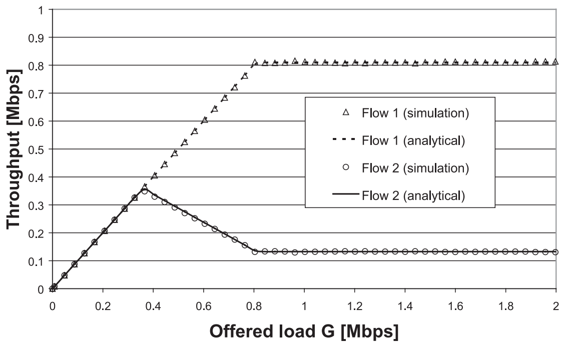

Fig. 4 Throughputs in RR scheduling.

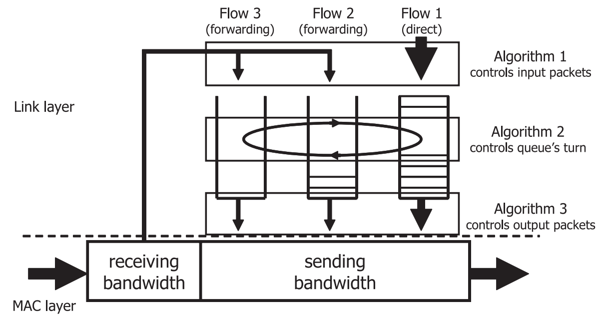

Fig. 5 Probabilistic control on round robin queue.

scheduling fails to achieve the fairness between the direct flow and forwarding flow. When the offered load increases, the throughput of the flow 1 comes to $B_1 - B_2$, while the throughput of the flow 2 comes to B_2 that is much smaller than the other. Figures 3 and 4 also show that our analysis is accurate: the simulation results coincide with the analytical results, in both FIFO and RR schedulings.

Thus, the good fairness in multihop ad hoc networks cannot be achieved by the only use of RR scheduling.

4. Probabilistic Control on Round Robin Queue Scheduling

The reason why RR mechanism cannot give a satisfactory throughput for forwarding flows is the limited receiving bandwidth at the MAC layer. Only a small number of forwarding packets can reach the relay station, the forwarding flow's queues often become empty and thus RR mechanism misses turns for forwarding flows. It is clearly of great advance to the direct flow. Our idea is to manage RR queues to ensure fair buffer and bandwidth allocation.

We now propose Probabilistic Control on Round robin Queue (PCRQ) scheduling. In PCRQ scheduling, RR queues are used with three algorithms: Algorithm 1 controls the number of input packets to queues, Algorithm 2 controls the turn of reading queues, and Algorithm 3 controls the number of output packets from queues. Figure 5 shows our proposed method.

4.1 Algorithm 1 (Controlling the Number of Input Packets to Queues)

In multihop network, when the offered load is large, the direct flow's queue tends to occupy completely the buffer space. Algorithm 1 decides to receive or to drop an input packet so as not to put too much packets to a queue. An arriving packet from flow i is put into its queue at the following probability;

$$P_{i\_input} = \begin{cases} 1, & \text{if } qlen_i \le ave \\ 1 - \alpha \dfrac{qlen_i - ave}{(n-1)ave}, & \text{if } qlen_i > ave \end{cases} \tag{5}$$

where α is an input weight constant, ave is the average of the queue lengths for all flows, n is the number of flows, $qlen_i$ is the queue length of flow i. Packets from a heavy offered load flow may be dropped with probability in range 0 to α. In case the queue of flow i is full while other queues are empty, income packet will be dropped with probability α. In case the queue length of flow i smaller or equal average queue length, all packets will be enqueued. Algorithm 1 reduces input packets of a flow with heavy offered load and makes the queue length of each flow fairer and smaller.

4.2 Algorithm 2 (Controlling the Turn of Reading Queues)

Generally, the receiving bandwidth is small, thus the forwarding flow's queues often become empty. In this case, the direct flow will get more turns from RR mechanism, and good per-flow fairness is not ensured. Algorithm 2 keeps the empty queue's turn for an interval time δ and waits for a new packet. The queue's turn of flow i is hold at the following probability;

$$P_{i\_turn} = \begin{cases} \beta \dfrac{qmax}{n \cdot ave}, & \text{if } qlen_i = 0 \\ 0, & \text{if } qlen_i > 0 \end{cases} \tag{6}$$

where β is a hold weight constant, $qmax$ is the maximum queue length of all queue. The turn of the empty queue is kept with probability in range β/n to β. In case a queue is full while other queue are empty, the turn of the empty queue is kept with probability β. In case the queue lengths of all flow are almost equal, this probability is about β/n. Because a delay time δ can be used for receiving packets, the receiving bandwidth at the MAC layer will be improved. Thus, Algorithm 2 does not only helps RR mechanism working more effectively but also makes the receiving and sending bandwidths fairer.

4.3 Algorithm 3 (Controlling the Number of Output Packets from Queues)

The unfairness between the receiving and sending bandwidths is the main reason of per-flow unfairness in RR scheduling as in Sect. 3. Algorithm 3 prevents heavy offered load flows from sending many packets to the MAC layer, and more bandwidth is left for receiving forwarding flows. Thus, throughputs of forwarding flows are improved.

A packet at the head of the queue for flow i is sent from the link layer to the MAC layer at the following probability;

$$P_{i\_output} = \begin{cases} 1, & \text{if } qlen_i \le ave \\ 1 - \gamma \dfrac{qlen_i - ave}{(n-1)ave}, & \text{if } qlen_i > ave \end{cases} \tag{7}$$

where γ is an output weight constant. Packets from a heavy offered load flow may be delay to send with probability in range 0 to γ. In case the queue is full while other flow is empty, packets may stop sending with probability γ. In case the queue length smaller or equal average queue length, all packets will be dequeued. If Algorithm 3 decides postpone sending a packet, the packet is delayed for an interval time δ. Thus Algorithm 3 not only makes the receiving and sending bandwidths fair, but also the throughput for each flow fair.

5. Performance Evaluation

We now evaluate the performance of PCRQ scheduling by comparing with the original FIFO scheduling in IEEE 801.11 standard, RR scheduling and Shagdar's method [5]. We use *Network Simulator* (NS-2) [7] for evaluation. The simulation parameters are shown in Table 2. In PCRQ scheduling, we set the input weight constant $\alpha = 2.0$, the hold weight constant $\beta = 0.3$, the output weight constant $\gamma = 0.3$ and delay time $\delta = 1$[ms]. Four types of scenarios are used to evaluate the performance of PCRQ scheduling. Scenario-1 is a long chain of stations. The complicated MAC layer contention is examined in the Scenario-2. Scenario-3 is used to examine the contention between UDP and TCP flows. The bandwidth utilization is examined in case each station generates different offered load in the last scenario.

In our simulation, the following four important performance metrics are evaluated.

- Fairness index: We use the fairness index, which is defined by R. Jain [22] as follows:

$$\text{Fairness Index} = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} x_i^2} \tag{8}$$

  where n is the number of flows, x_i is the throughput of flow i. The result ranges from $1/n$ to 1. In the best case, throughput of all flows are equal, the fairness index achieves 1. In the worst case, the network is totally unfair, one flow gets all capacity while other flows get nothing, fairness index is $1/n$. In this paper, fairness index is evaluated based on goodput at the destination station.
- Average queue length: The average of total queue lengths of all RR queues at the station during simulation.
- Average delay time: The average end-to-end delay time during simulation of all packets, which successfully reached the destination.
- Total throughput: The average of total goodput of all flows during simulation.

Table 2 Parameters in the simulation.

Channel data rate	2[Mbps]
Antenna type	Omni direction
Radio Propagation	Two-ray ground
Transmission range	250[m]
Carrier Sensing range	550[m]
MAC protocol	IEEE 802.11b (RTS/CTS is enable)
Connection type	UDP/CBR and TCP/FTP
Buffer size	100[packet]
Packet size	1[KB]
Simulation time	100[s]

5.1 Scenario-1

Scenario-1 includes a chain of five stations with four flows. The coordinates of stations are shown in Fig. 6. The stations M1, M2, M3 and M4 generate UDP or TCP traffic to gateway GW. To examine UDP traffic, we consider all stations generate at the same offered load G. The performance metrics is evaluated versus the offered load G.

Fairness indices in UDP traffic are shown in Fig. 7. When the offered load is small, all scheduling methods get perfect fairness index. When the offered load becomes larger, because a common queue is used in FIFO scheduling, the direct flow gradually occupies completely the buffer space and the fairness index becomes very bad. In RR scheduling and Shagdar's method, even different queue is used for each flow, but the receiving packets from the forwarding flow are limited because of the MAC layer contention, resulting bad fairness indices. While, in PCRQ scheduling, the receiving and sending bandwidths at the MAC layer become fairer, and also the per-flow through-

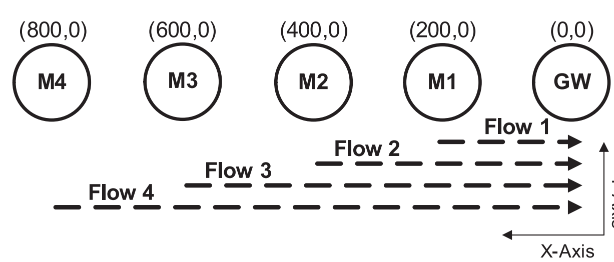

Fig. 6 Scenario-1: one five-station chain with four flows.

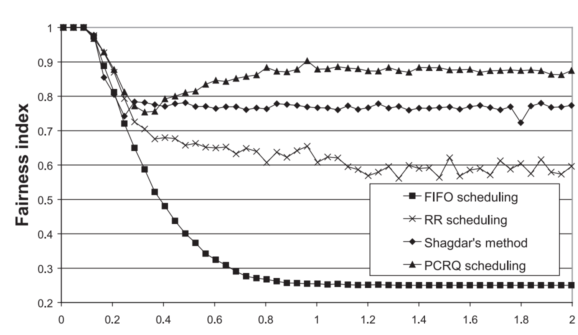

Fig. 7 Fairness indices for Scenario-1 in UDP traffic.

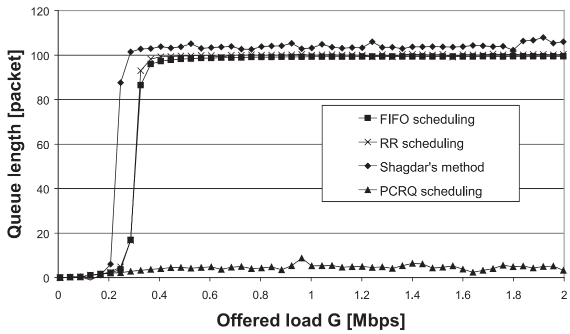

Fig. 8 Average queue lengths in station M1 for Scenario-1 in UDP traffic.

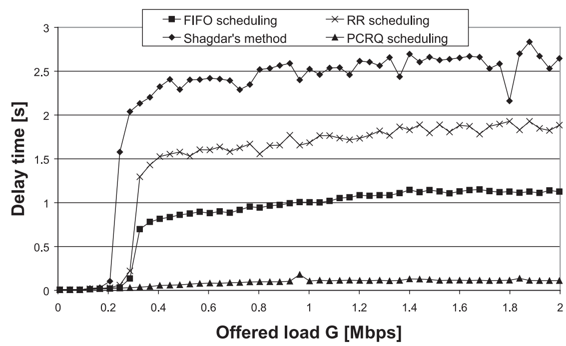

Fig. 9 Average delay time of flow 1 for Scenario-1 in UDP traffic.

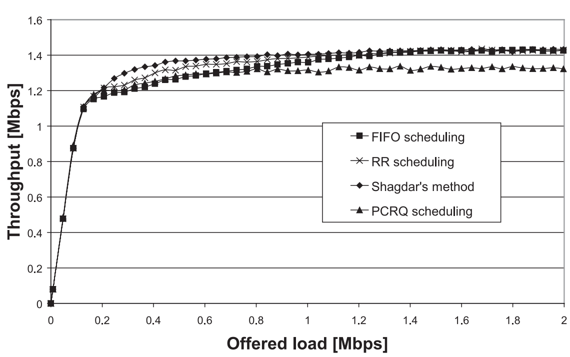

Fig. 10 Total throughput for Scenario-1 in UDP traffic.

put becomes fairer by Algorithms 2 and 3, the input offered load of each flow becomes fairer by Algorithm 1. Therefore, we get good fairness index.

The average total queue lengths of the direct and forwarding flows at station M1 in UDP traffic are shown in Fig. 8. When the offered load is small, the total offered load is smaller than the maximum medium bandwidth, and queue lengths are small in all the scheduling methods. When the offered load is larger, the common queue in FIFO scheduling and the direct flow's queue in RR scheduling and Shagdar's method will be full of packets. In PCRQ scheduling, input packets are controlled by Algorithm 1 that describes our queue length as the smallest among all the scheduling methods.

The average delay time of flow 1 in UDP traffic is

Table 3 The simulation results of TCP traffic in Scenario-1.

	FIFO	RR	Shagdar	PCRQ
Fairness index	0.464	0.553	0.487	0.771
Queue length [pkt][a]	24.011	7.775	6.040	1.707
Delay time [s][b]	0.255	0.079	0.087	0.029
Throughput [Mbps]	1.069	1.054	1.089	1.035

[a]The average total queue lengths of the direct and forwarding flows at station M1 in TCP traffic

[b]The average end to end delay time of flow 1 in TCP traffic

shown in Fig. 9. The average delay time is directly proportional to the average queue lengths. The average delay time in PCRQ scheduling is also smallest among all scheduling methods.

The total throughputs of all flows in UDP traffic are shown in Fig. 10. When the offered load is small, throughputs in all methods are similar. When the offered load becomes greater, PCRQ scheduling uses bandwidth slightly less efficiently than the others. The reason can be explained as follows. Algorithms 2 and 3 give delay to sending packets to give chance for receiving packets. However, if forwarding packets may not come, the next packet is taken longer time to transfer. Thus, our total throughput is slightly smaller than the other methods.

Table 3 shows the results in TCP traffic. Because TCP can adapt the window size to the network condition and reduce offered load of the direct flow. Thus, fairness in TCP traffic is better than in UDP traffic in FIFO scheduling. However, due to the MAC layer contention, only small number of forwarding packets can reach relay stations, fairness is not improved much in RR scheduling and Shagdar's method. In PCRQ scheduling, Algorithms 2 and 3 improve the receiving bandwidth. Therefore, our fairness index is better than the other methods. As the same reason above, other performance metrics as queue length, delay time in PCRQ scheduling also much better than the other methods. Total throughout are similar in all scheduling methods.

5.2 Scenario-2

Scenario-2 includes two chains of stations, one consists of three stations and the other consists of two stations. The coordinates of stations are shown in Fig. 11. The number of flows is four. The stations M1, M2, M3, and M4 generate UDP or TCP traffic to gateway GW. In this scenario, the MAC layer contention at station M1 is more complicated than in the previous scenario because there are more stations in the same transmission range with station M1.

The performance results in UDP traffic are shown in Figs. 12, 13, 14 and 15. The results show that PCRQ scheduling still gives better performance metrics in term fairness, queue length and delay time than the others. Moreover, the throughput performance is similar to the other methods.

The performance results in TCP traffic are shown in Table 4. PCRQ scheduling still archives good results in terms of fairness, queue length and delay time. Our total through-

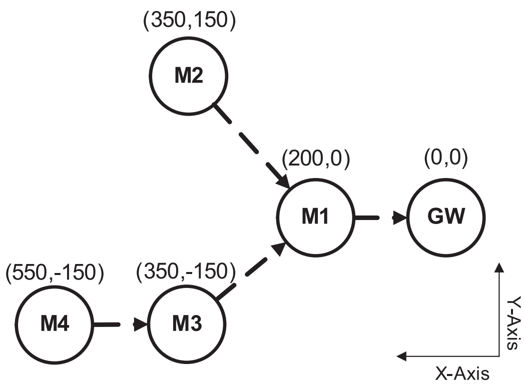

Fig. 11 Scenario-2: one three-station chain and one four-station chain with four flows.

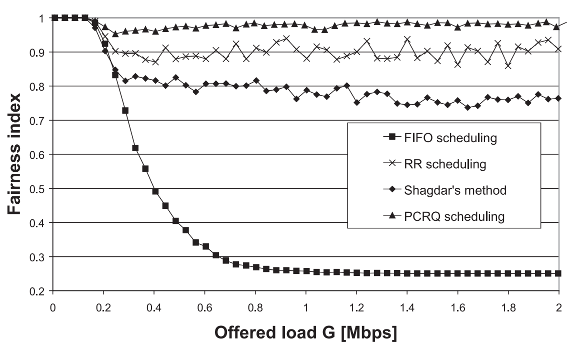

Fig. 12 Fairness indices for Scenario-2 in UDP traffic.

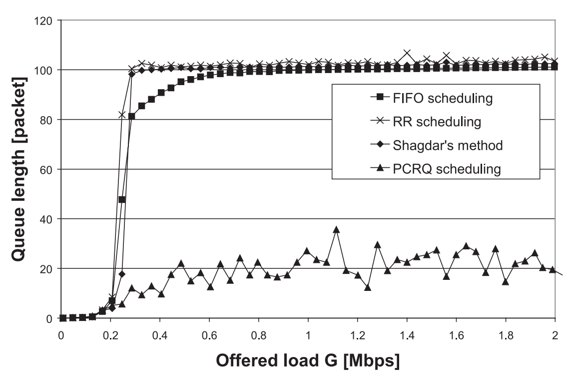

Fig. 13 Average queue lengths in station M1 for Scenario-2 in UDP traffic.

Table 4 The simulation results of TCP traffic in Scenario-2.

	FIFO	RR	Shagdar	PCRQ
Fairness index	0.653	0.659	0.708	0.746
Queue length [pkt]	35.727	36.181	6.026	2.273
Delay time [s]	0.393	0.394	0.099	0.036
Throughput [Mbps]	1.069	1.070	1.098	1.060

put is slightly smaller as the trade-off between fairness and throughput.

In this scenario, the fairness result is better than in Scenario-1 for all scheduling methods. The reason can be explained as follows. Two stations M2 and M3 compete for bandwidth with station M1 in Scenario-2, while there is only one station M2 in Scenario-1. Thus, station M1 achieves a little smaller bandwidth than in Scenario-1, and the MAC layer unfairness at station M1 is slightly reduced compared to Scenario-1. It makes fairness performance in Scenario-2 higher than in Scenario-1.

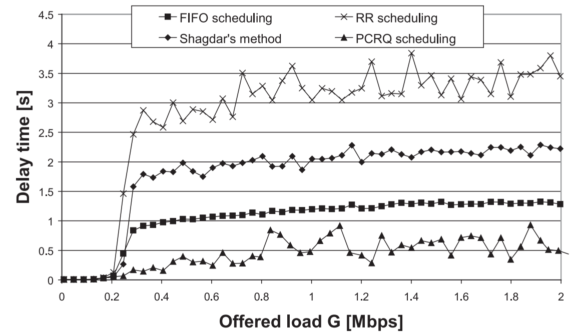

Fig. 14 Average delay time of flow 1 for Scenario-2 in UDP traffic.

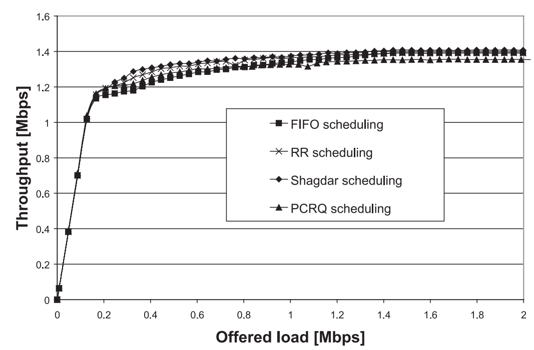

Fig. 15 Total throughput for Scenario-2 in UDP traffic.

5.3 Scenario-3

Scenario-3 is created to examine the contention between UDP and TCP flows. The coordinates of stations are shown in Fig. 16. These are one UDP flow from station M2 and two TCP flows from stations M3 and M4 respectively. The UDP flow's offered load is set equal to channel data rate.

The performance results are shown in Table 5. PCRQ scheduling achieves better fairness index than other methods also in case of mixed UDP and TCP. PCRQ scheduling also achieves good result in terms of queue length. The fairness index of this scenario as in Table 5 is better than previous scenarios in Tables 3 and 4. This reason is that stations M2, M3 and M4 are fairer in the MAC layer contention in Scenario-3, while the MAC layer contentions are harder because of asymmetric stations' location in Scenarios-1 and 2.

5.4 Scenario-4

Scenario-4 is used to examine bandwidth utilization in case each station generates different offered load. We use the basic multihop network model as in Fig. 1. Stations M1 and M2 generate UDP traffic with two cases:

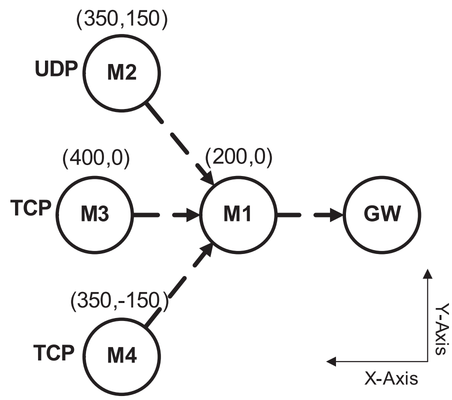

Fig. 16 Scenario-3: Five-station with one UDP flow and two TCP flows.

Table 5 The simulation results in Scenario-3.

	FIFO	RR	Shagdar	PCRQ
Fairness index	0.909	0.921	0.948	0.968
Queue length [pkt]	37.342	51.150	3.329	2.55
Throughput [Mbps]	1.206	1.201	1.162	1.194

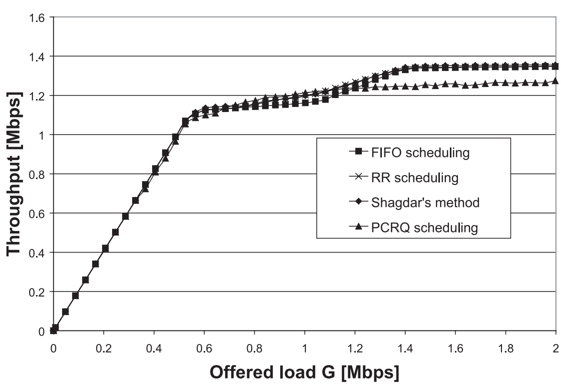

Fig. 17 Total throughput for Scenario-4 in Case-1.

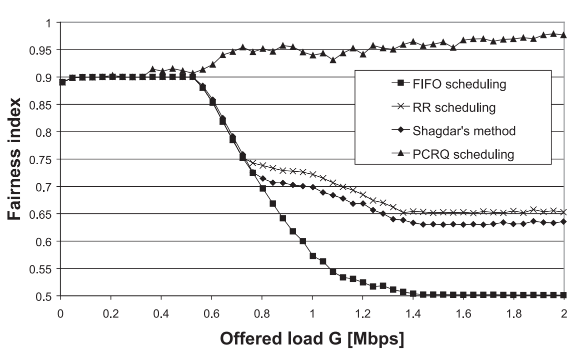

Fig. 18 Fairness indices for Scenario-4 in Case-1.

- Case-1: The offered load of flow1 is G, while the offered load of flow2 is $G/2$.
- Case-2: The offered load of flow1 is $G/2$, while the offered load of flow2 is G.

The simulation results in total throughput are shown in Figs. 17 and 19. Consider Case-1, where station M1 generates twice as much offered load as station M2. When G is small, each station can achieve maximum throughput in all scheduling methods. Even each station has different offered load, the utilization in PCRQ scheduling is not affected because our algorithms operate based on queue length. When G becomes larger, our throughput is slightly smaller than the other method because our algorithms try to reduce the throughput of flow 1 to give chance for flow 2.

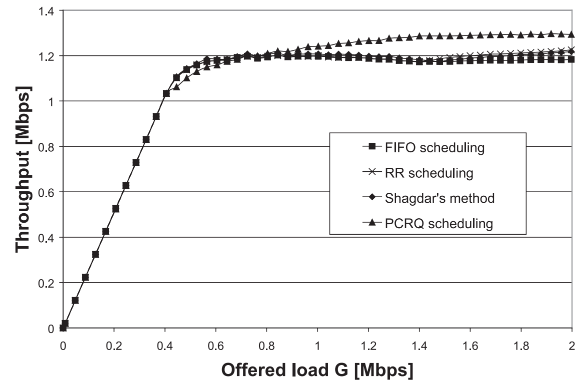

Fig. 19 Total throughput for Scenario-4 in Case-2.

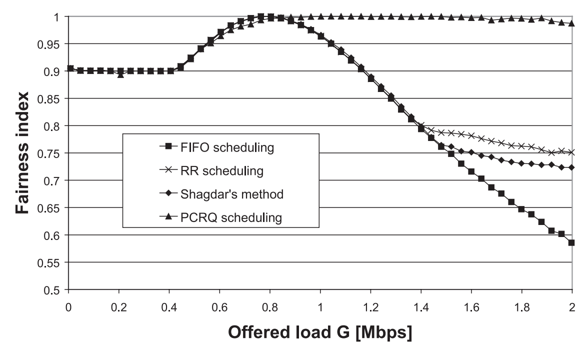

Fig. 20 Fairness indices for Scenario-4 in Case-2.

Consider Case-2, where station M1 generates half as much offered load as station M2. In this case, PCRQ scheduling achieves better throughput than other method when G becomes larger. Our algorithms also reduce the throughput of flow 1. However, the throughput of flow 2 much improved due to the offered load of flow 2 is higher than in Case-1. Thus, in total throughput, PCRQ scheduling is better than the others.

Fairness indices in Cases-1 and 2 are shown in Figs. 18 and 20, respectively. When G is small, fairness indices of all methods are the same in both Cases-1 and 2. When G becomes larger, fairness indices of PCRQ scheduling are improved in both Cases-1 and 2 because the light throughput flow has a better chance for sending packets than the heavy throughput flow by the operation of our Algorithms.

While in the other methods, the direct flow becomes more advantageous for sending packets than the forwarding flow when G becomes larger. In Case-1, the offered load of flow 1 is two times greater than flow 2, of course, flow 1 will fast starve the bandwidth, thus their fairness indices decrease (see Fig. 18). In Case-2, even the offered load of flow 2 is two times greater than flow 1, the throughput of flow 1 still gradually increases while the throughput of flow 2 decreases. When the offered load G is around $0.8[Mbps]$, the throughput of flow 1 is equal to flow 2 and the fairness indices is equal to 1 (see Fig. 20). However, their fairness indices will fast decrease because the throughput of flow 1 continues increasing.

In case of a heavy offered load, PCRQ scheduling gives a delay for a packet from heavy flows. Meanwhile, PCRQ scheduling greatly improves fairness performance even in the case of asymmetric topologies, and ensures a sustainable throughput for long-hop flows. Due to the absence of global scheduling in the IEEE 802.11 [1], there exists a trade-off between the fairness and the throughput performances. PCRQ scheduling improves the fairness index by up to 70% compared to the other methods, while the difference of throughputs between PCRQ scheduling and the other methods is smaller than 6% which is acceptable. In addition, PCRQ scheduling also achieves better performance in delay time and buffer utilization than the other methods.

6. Discussion on Parameter Values

Our Algorithms's target is to improve network performance in IEEE 802.11 [1] multihop wireless network. Algorithm 1 controls input packets and queue length of each flow become fairer due to dropping some packets from a flow with the heavy input offered load. Eq. (5) showed Algorithm 1's operation. The larger value of the input weight constant α is, the more packets are dropped from the heavy offered load flow. Algorithm 1 tries to reduce queue length of the heavy offered load flow to make it reduce to the average queue length and Algorithm 1 stops to drop packets when the queue length is smaller than the average queue length. Thus, α can greater than 1. In our simulations, we chose α equal to 2.

Algorithm 2 only makes a delay for waiting a new packet to an empty flow. Thus, the hold weight constant β also can be greater than 1. However the greater value of β is, the longer delay time is. It is not good for bandwidth utilization. To avoid processing finished flows, we need to determine when a flow finishes by using a timeout. If a flow is empty over a timeout, its queue is removed from RR queues. In our simulations, we chose β equal to 0.3.

Algorithm 3 makes a delay for sending a packet based on queue length. It leads to increase queue length, with the result that P_{output} decreases. Thus the output weight constant γ must be smaller than 1, otherwise P_{output} becomes zero and no packet can be sent. Algorithms 1 and 3 are pair algorithms that affect to queue length. Algorithm 3 may delay for sending packets and the queue length may increase. In opposite, Algorithm 1 reduces the queue length by dropping packets. These algorithms help queue length get stable. The same reason with Algorithm 2, the large value of γ may degrade bandwidth utilization. In our simulations, we chose γ equal to 0.3.

7. Conclusion

In this paper, we proposed a new scheduling method to improve the fairness in multihop wireless ad hoc networks and compared it to conventional methods. FIFO scheduling has only one queue; therefore, it cannot solve the unfairness problem by the link layer contention. RR scheduling and Shagdar's method also work ineffectively because the allocated bandwidths at the MAC layer are not suitable for forwarding and direct flows in the link layer. We proposed the PCRQ scheduling in the link layer to solve these problems. By controlling input/output packets to/from a queue and turns of reading queues in RR fashion, PCRQ scheduling controls the contention at the MAC layer indirectly. Our Algorithms improved per-flow fairness and helped RR mechanism work more effectively. In addition to fairness, the queue length in PCRQ scheduling was smaller; it results in less buffer resource than the other methods. Moreover, our delay time was also lower than the others. Therefore, it is useful for services, which require real-time packet transmission. Since PCRQ scheduling works on the link layer, it is easy to implement without changing hardware.

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